Sensing and Awareness in Microsystems

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Report Documentation Page

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Chip-Scale Atomic Devices

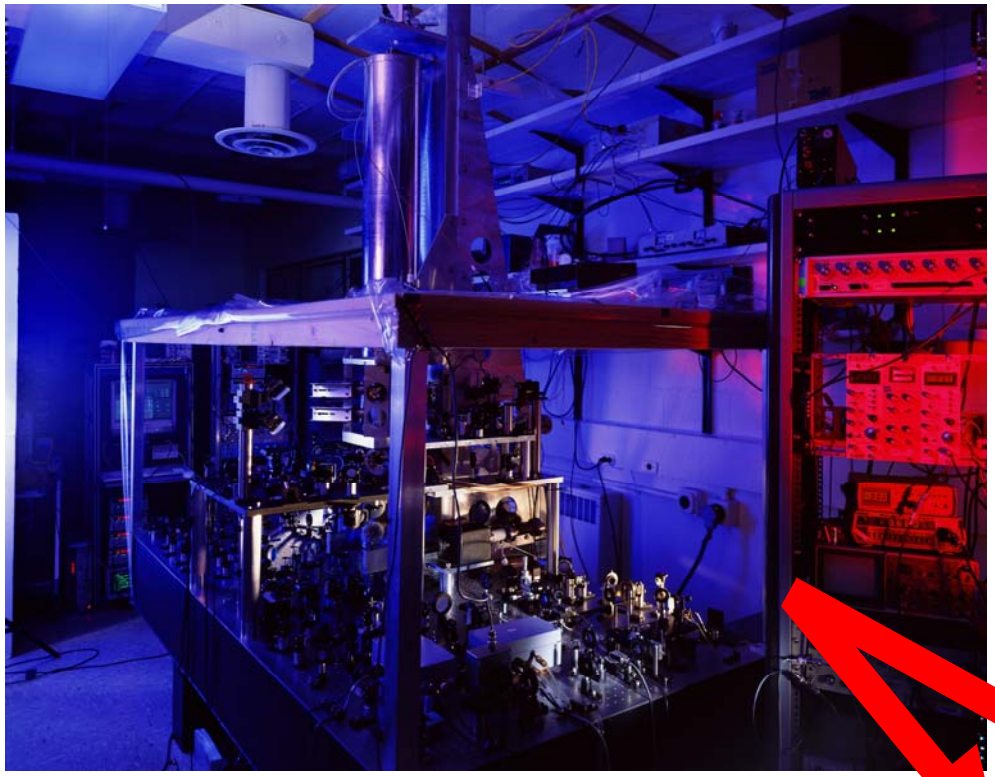
Precision Instruments based on Lasers, Atoms and MEMS

John Kitching

Time and Frequency Division
NIST

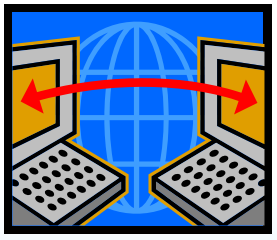
Microsystems Technology Symposium
San Jose, CA, March, 2009

Atomic Clocks

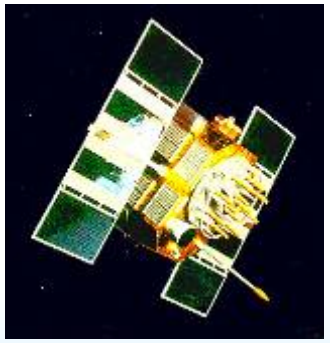


NIST F-1 Primary Atomic Frequency Standard

- Time: most accurately measured physical quantity
- NIST: most accurate clock in the world
  - Frequency uncertainty ~ 4×10^{-16}
  - Timing instability < 1 ns over 1 week



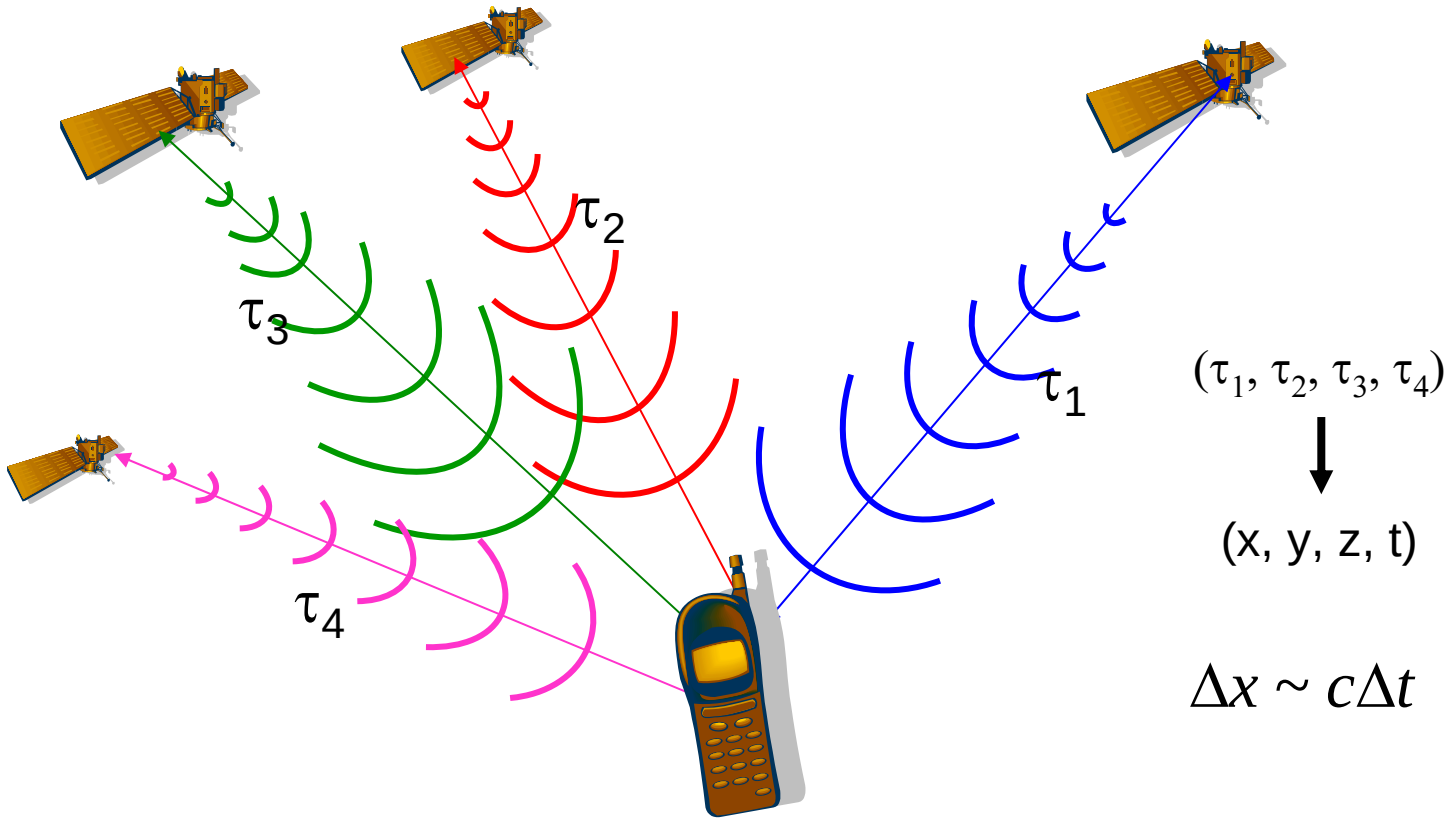
Telecom Sync



GPS System

Precision is a Big Deal

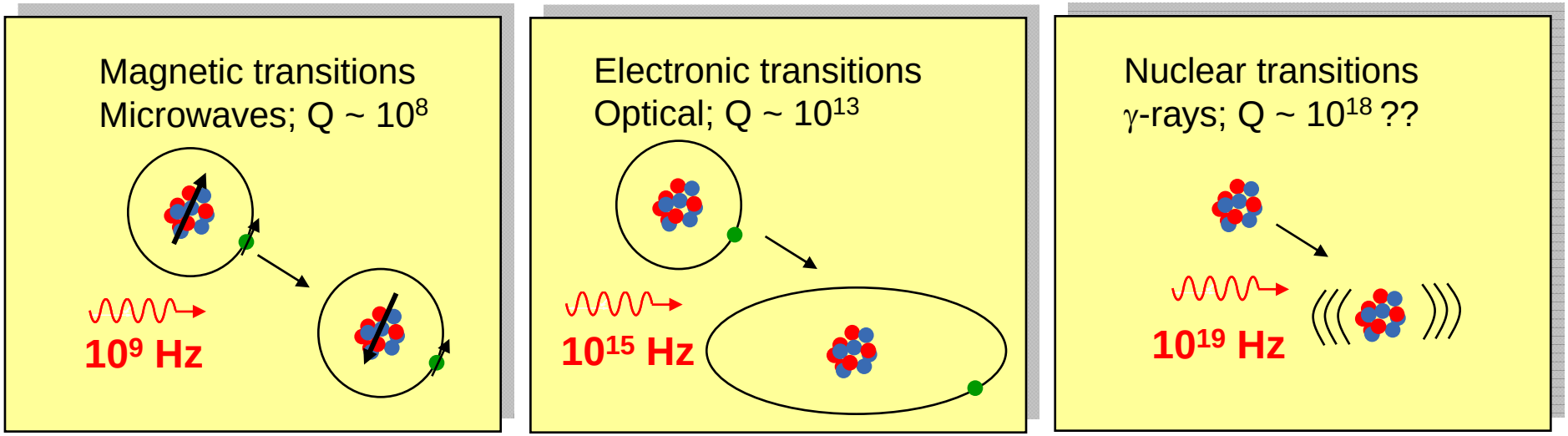
- Speed of light: 30 cm/ns



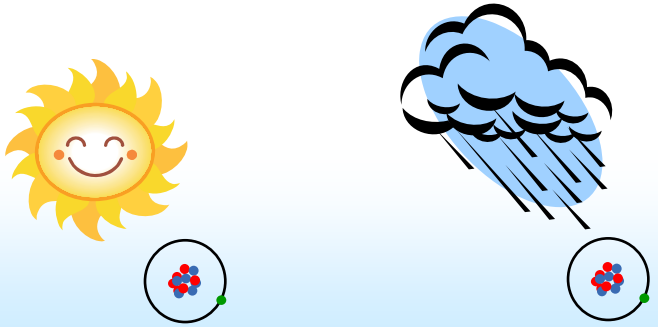
- Positioning to 1 m ⇒ ns timing required
- Positioning to 1 mm ⇒ ps timing

Origin of the Precision?

- High frequencies, long coherence times

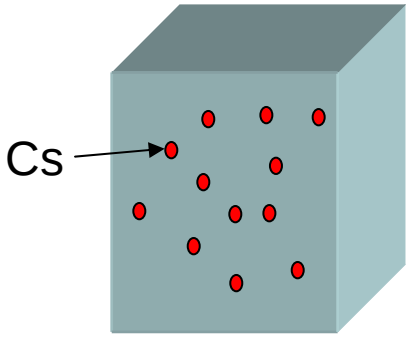


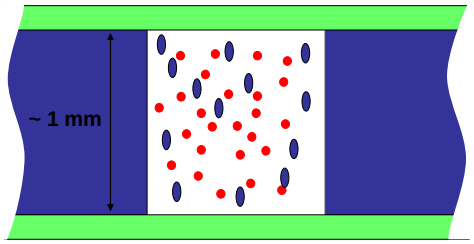
- High signal-to-noise
  - Spectroscopic measurements and/or large numbers of atoms
  - As high as 10^7 @ 1 sec
- Insensitive to environment

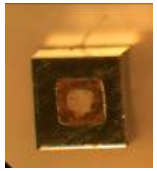


MEMS Fabrication

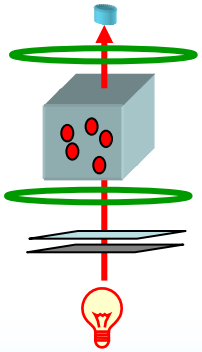
- Alkali atom vapor cells

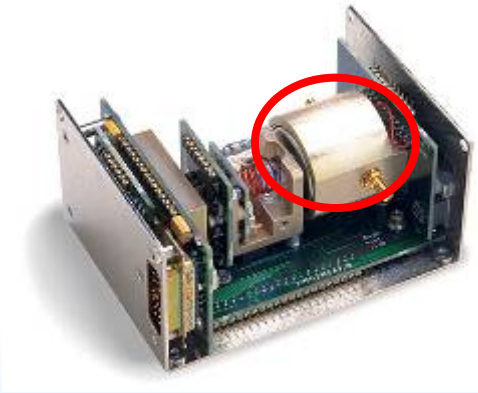


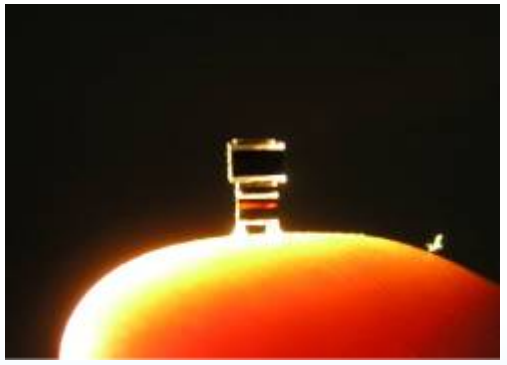




- Atomic clock physics packages





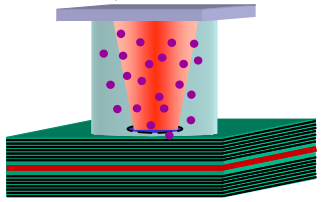


CSAC Program

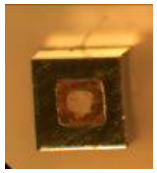
Guided by: Bill Tang … Clark Nguyen … Amit Lal …

Phase I | Phase II | Phase III | Phase IV

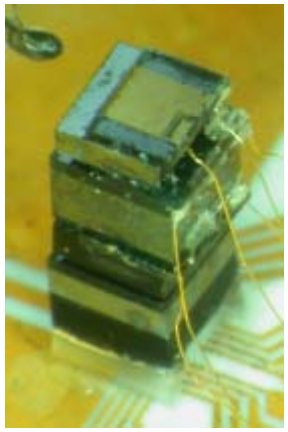
2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009



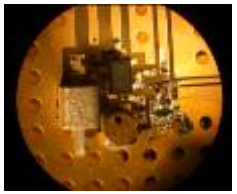
Concept
DARPA/NIST



Cells
NIST

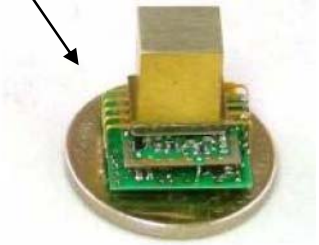


Physics Package
NIST



Oscillators
CU

Integrated
electronics
Symmetricom,
Honeywell

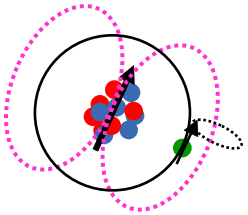


1cc instrument
Teledyne
Symmetricom

- Ruggedization
- Manufacturing
- Applications

V ~ 1 cm^3
P ~ 30 mW
$\Delta f/f \sim 10^{-11}$ @ 1 hr

Beyond CSAC: Magnetometers

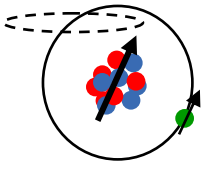


B_N

$\omega_{hf} \propto B_N = const$

Clocks

B_0



$\omega_L \propto B_0$

Mags

Sensitivity fT/√Hz

10^{11}

Hall

10^6

MR

10^4

Flux Gate

10^3

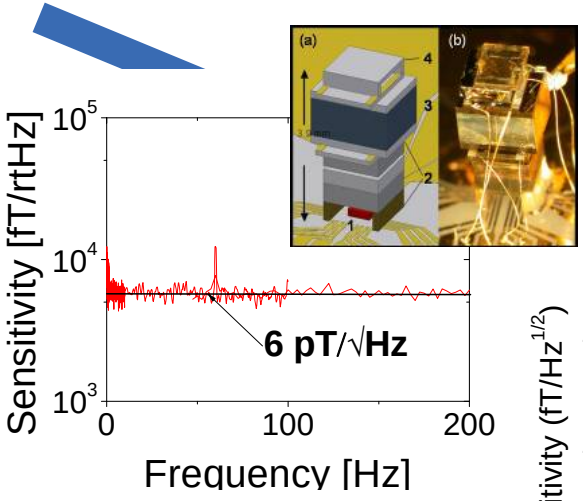
Atomic

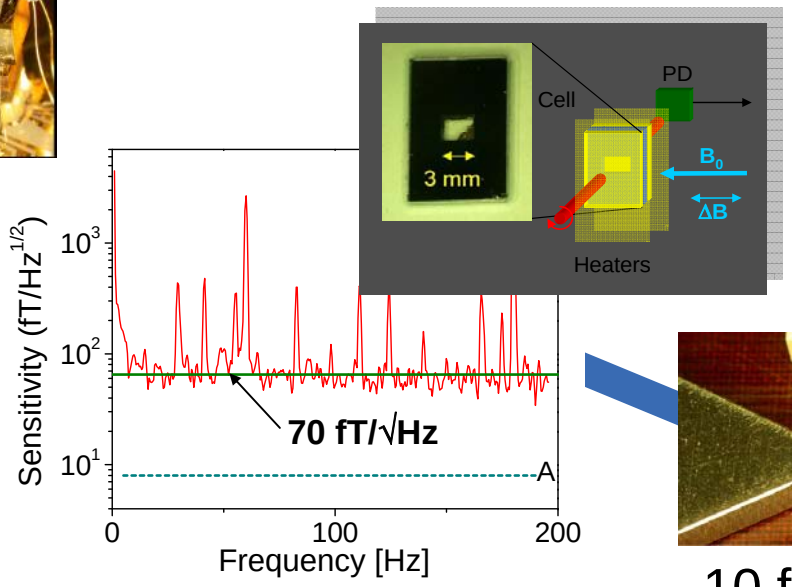
100

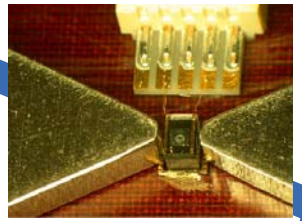
10

SQUID

1







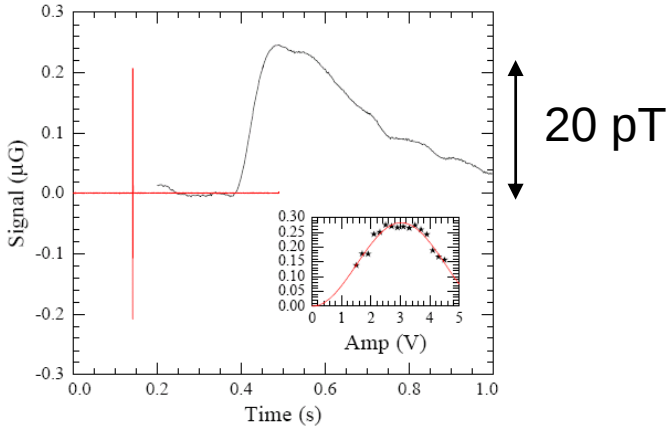
10 fT/√Hz

SQUID sensitivity ~~Cryogenics~~

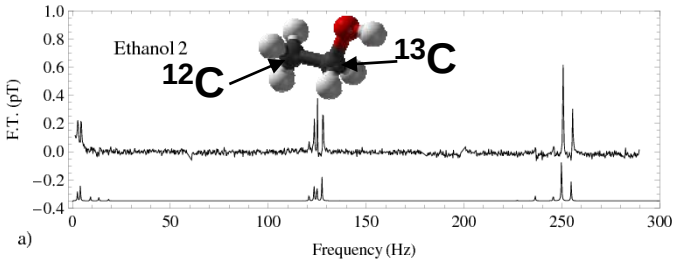
Microfluidic NMR

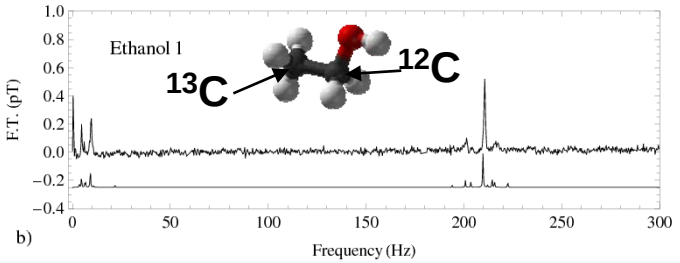
With A. Pines, D. Budker, UC-Berkeley

M. Ledbetter, et al., PNAS, **105**, 2286, 2008



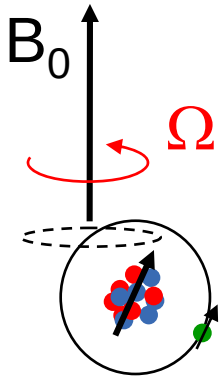
20 pT





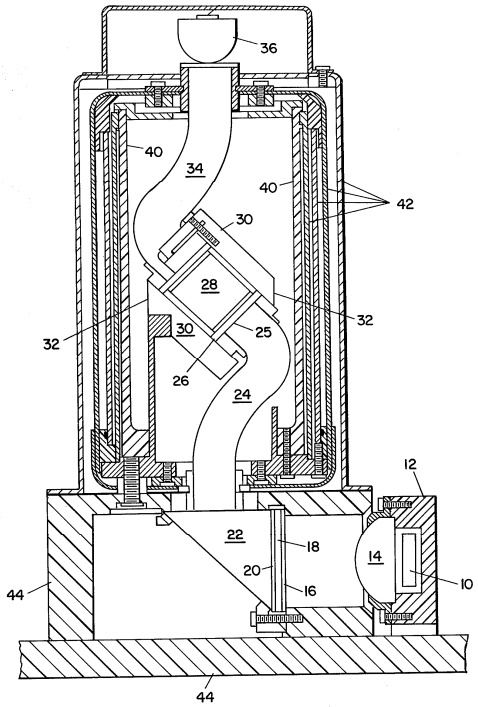
NMR at zero field: simple spectra, compact apparatus

Beyond CSAC: Gyroscopes



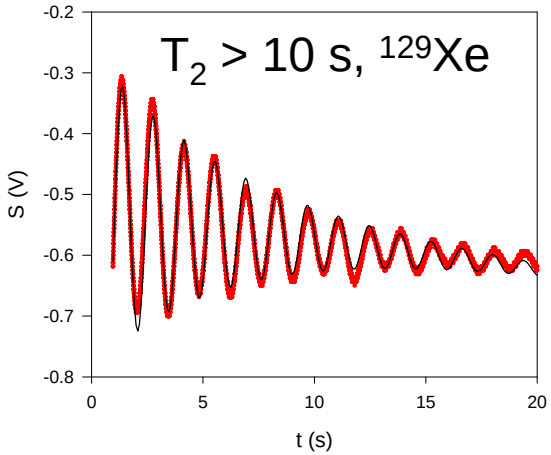
$$\omega_L = \gamma B_0 + \Omega$$

Nuclear spins
- Longer coherence time
- Lower field sensitivity
- ^{129}Xe, ^{21}Ne, ^{199}Hg…
- Read out precession with alkali magnetometer



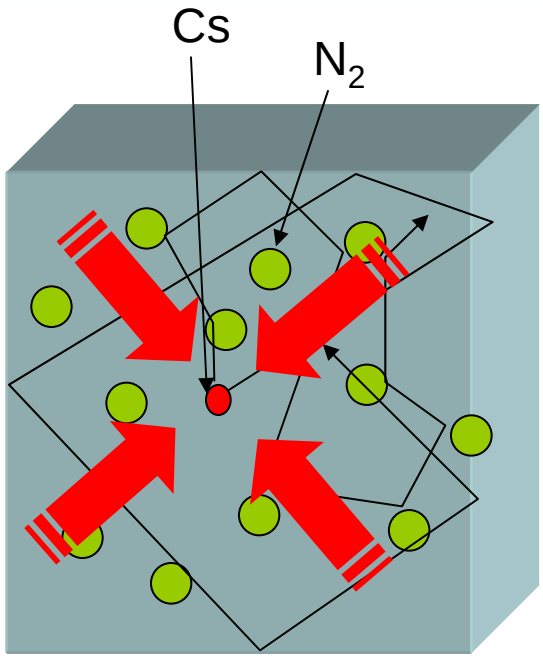
Litton, 1979
1000 cm^3, 0.1 °/hr

+ MEMS



DARPA NGIMG:
1 cm^3, 5 mW, Nav-grade

Laser-Cooled Atoms



V_{at} ~ 500 m/s → 1 cm/s
~ 1 μs/cm → T_c ~ 1 s

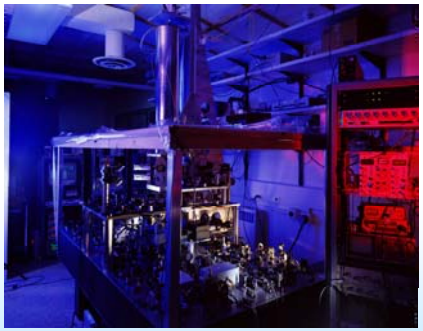
- Wall coatings
- Buffer gases
- Laser cooling

Nobel Prize (1997)
C. Cohen-Tannoudji,
W. D. Phillips, S. Chu

Fountain clocks
Atom interferometers
- Gyros
- Gravimeters, accelerometers
- Magnetometers

Bose-Einstein condensates

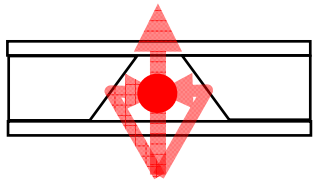
$\Delta t/t \sim 10^{-16}$
$\Delta\Omega/\Delta t \sim 10^{-6}$ °/hr
$\Delta x/\Delta t \sim 5$ m/h
$\delta B/dx \sim 10$ fT/√Hz/mm



DARPA
gBECi
PINS
(DSO)

1 m

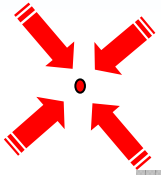
w/ MTO ?



1 cm ?
5 mW ?

DARPA IMPACT, CSVMP

Chip-Scale Atomic Devices: 2001-2009



PINS
gBECi

IMPACT
CSMVP

DARPA

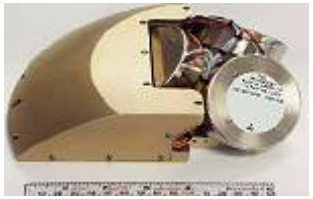
MTO MEMS

CSAC

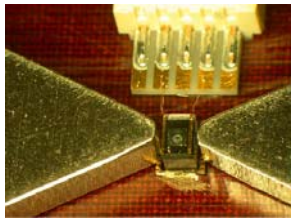
NGIMG

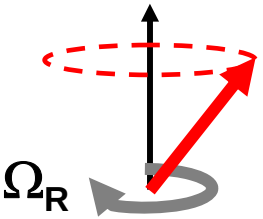
DARPA

MTO MEMS

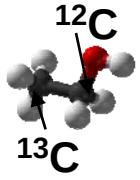


Conventional
Atomic Devices

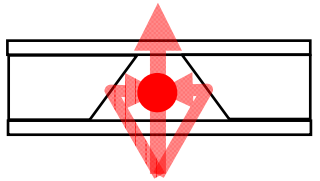




Chip-Scale
Atomic Devices
100 X smaller



Applications



Micro Laser-Cooled
Systems
1000 X better


MICROSYSTEMS TECHNOLOGY OFFICE
MTO
DARPA
SYMPOSIUM
BUILDING THE FUTURE
FROM THE INSIDE OUT
Approved For Public Release, Distribution Unlimited